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Title:	Diagnosing Thermonuclear Burn in Fusion Implosions using Ultra-Fast Gas Cherenkov Detectors
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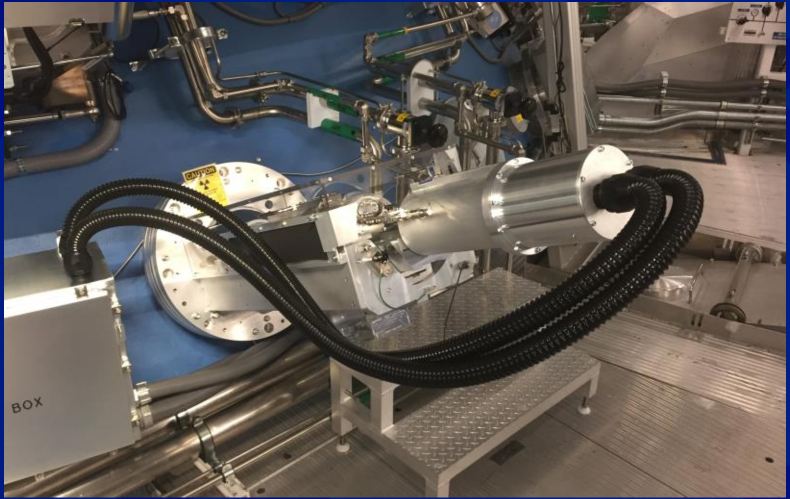
Diagnosing Thermonuclear Burn in Fusion Implosions using Ultra-Fast Gas Cherenkov Detectors

Hermann Geppert-Kleinrath, P-4

8/19/2021

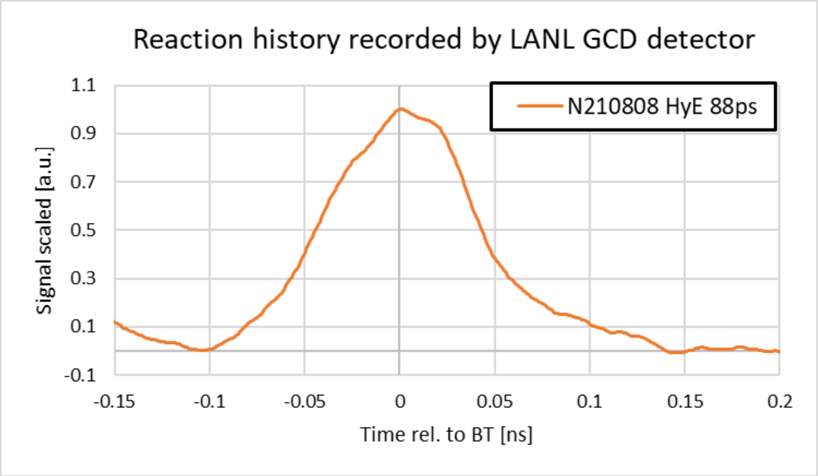


Gas Cherenkov Detector coupled with a Pulse Dilation - PMT at NIF

Record setting shot N210808 HyE at NIF last week

Data suggests that this shot might have reached **~1 MJ** yield and burn **propagation**.

- ~4E17 neutron yield
- ~1MJ energy yield
- ~6x more yield than ever
- ~4x times more energy yield than energy absorbed by the capsule
- ~88 ps burn width



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LANL funding provided by C-10 Inertial Confinement Fusion

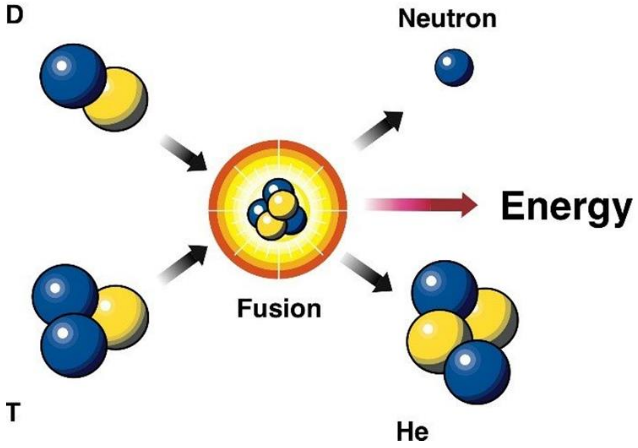
Outline:

- What is fusion and what is ignition?
- How does LASER driven Inertial Confinement Fusion work?
- What can we measure and what does it tell us about fusion?
- How do Gas Cherenkov detectors work and what do they tell us?
- What are our plans for the future?

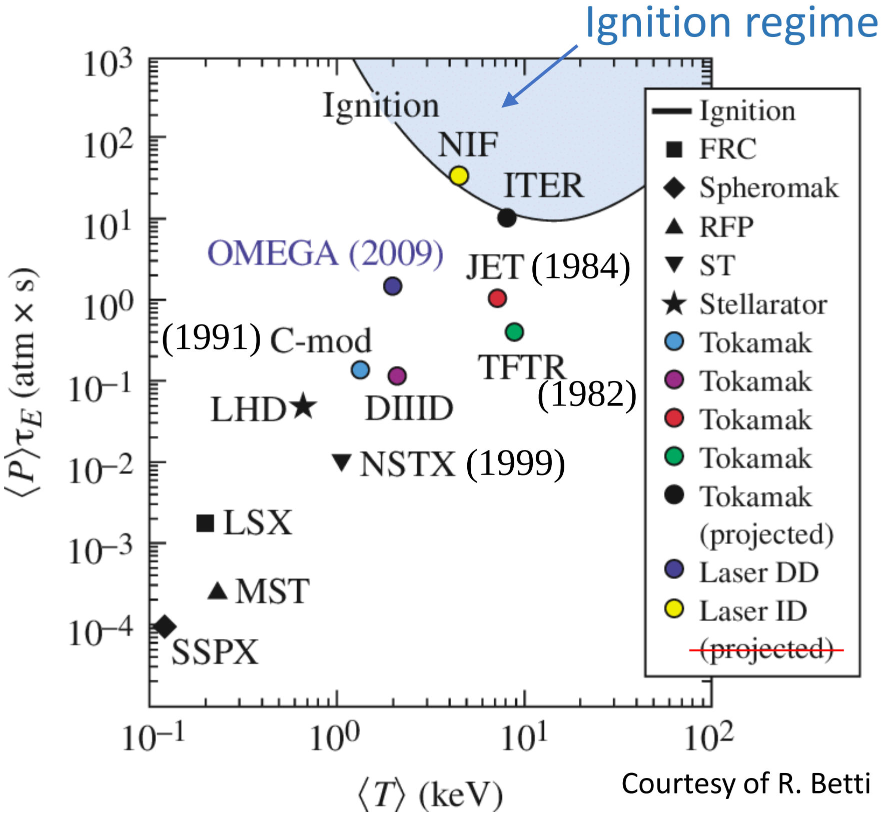
Take away:

- DT fusion reaction history provides crucial physics for ICF
- Gamma reaction history diagnostics are ready to resolve burn width on ignition shots
- GCDs have a lot of potential solving some of the questions related to fusion science

Decades of fusion research progress: Racing towards our shared goal of ignition

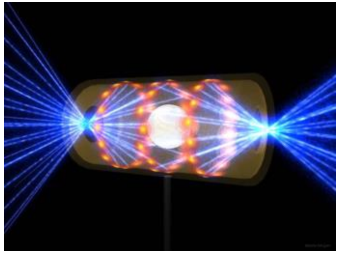


D + T $\rightarrow$ α (3.5 MeV) + n (14.1 MeV),
Q = 17.6 MeV

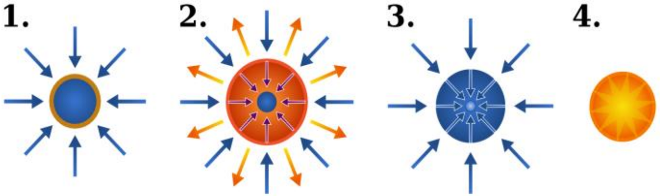


Courtesy of R. Betti

What is Inertial Confinement Fusion (ICF)



How we make a tiny sun:



1. Laser-produced x-rays heat a DT-filled fuel capsule
2. Capsule shell burns off
   → ablation (rocket drive)
3. Rapid compression and shock propagation
4. Fusion!

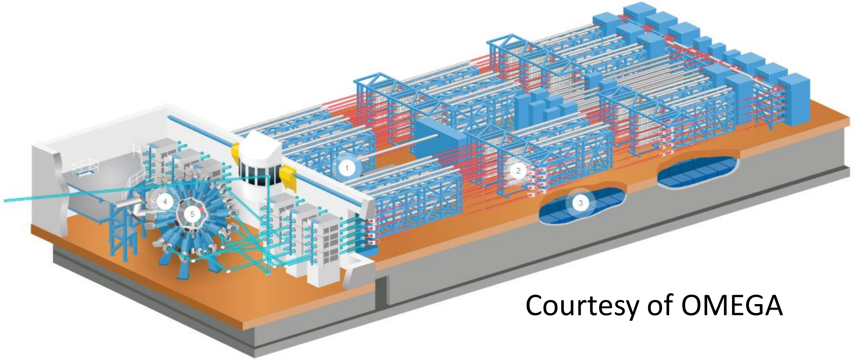
Two types of laser driven ICF:

- Direct Drive (laser directly on capsule)
- Indirect Drive (laser heat a Hohlraum → x-rays drive the capsule)

There are other ICF concepts:

- Z-pinch, Plasma Liner Experiment (PLX),…

Direct drive OMEGA laser facility, Rochester NY



70m long
60 beams
30kJ energy

Indirect drive National Ignition Facility, Livermore CA

Courtesy of NIF

260m long
192 beams
2MJ energy
12m diameter target chamber

ICF: “Creating a Star on Earth!”

NIF produces ~500 TW of UV laser light for several billionths of a sec (ns)

- The US electrical energy consumption is only ~0.5 TW (0.1% of NIF)
- NIF delivers 1.8 MJ of energy (430 nutritional calories = 1 jelly donut)

ICF spherical convergence leads to:

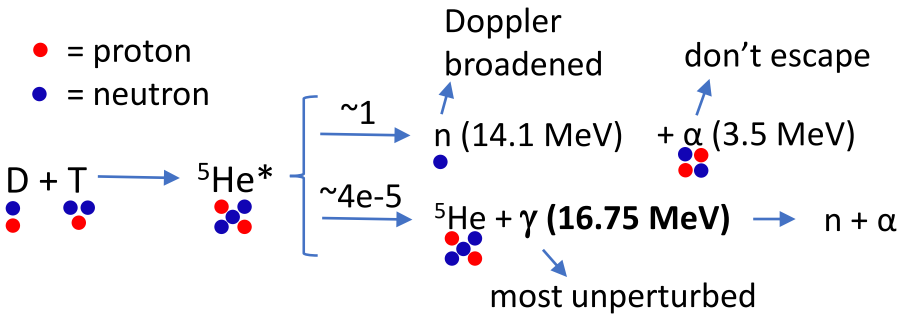
- Inward shell velocity ~300 km/s (that’s ~0.1% the speed of light!)
- Temp ~ 50M °C (~3x temp of sun’s center), or 100’s M °C if ignited
- Pressure ~ 400 Gbar (that’s nearly half a trillion atmospheres!)
- Duration ~150 ps (light only travels 4.5cm in that time) (~90 ps last week)

Current DT Fusion yields are:

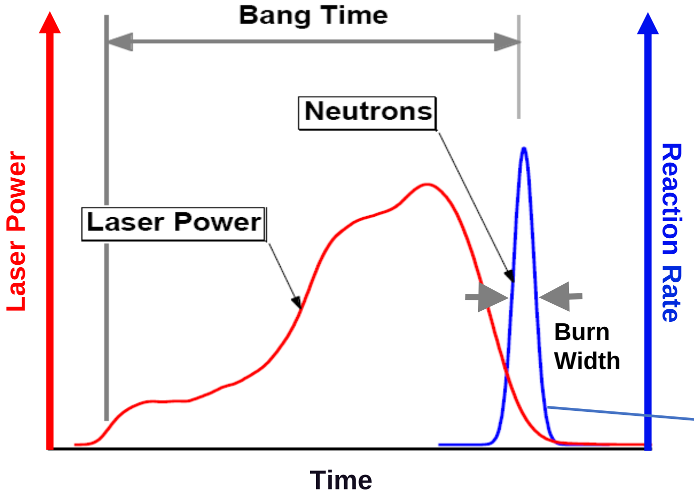
- ~2e16 n = ~55 kJ = ~1/20th of 1MJ (i.e., “Ignition”) = 10 μton TNT (2020)
- ~4e17 n = ~1 MJ last week
- NIF has succeeded at demonstrating moderate alpha heating (~2x)
- Now alpha heating seems to dominate

How to measure fusion burn history?

- Neutron signal is broadened by the Doppler effect. Neutron time of flight allows for yield and burn integrated ion temperature measurement.
- Alpha particles are charged and heavy. Alphas heat the hotspot (alpha heating) and will provide the energy going into a ignition regime.
- Gammas are the most unperturbed signal from DT fusion reactions. Detailed features of the fusion burn can be resolved.



DT gamma reaction history provides crucial information for inertial confinement fusion



DT fusion reaction history

Gammas directly from burn provide reaction history:

Bang Time → Simulations forced to match by compensation factors

Burn Width → Not matched in simulations while X-ray and DT data are in agreement

Burn Profile → New capability

Bang Time: Important for benchmarking simulations
Measurement of energy absorbed in the capsule

Burn Width: Duration of thermo-nuclear condition
Information on assembly and disassembly process

Burn Profile: Simulations can be matched to shape of reaction history
Gives tighter limits for simulations

Diagnosing ignition with DT reaction history

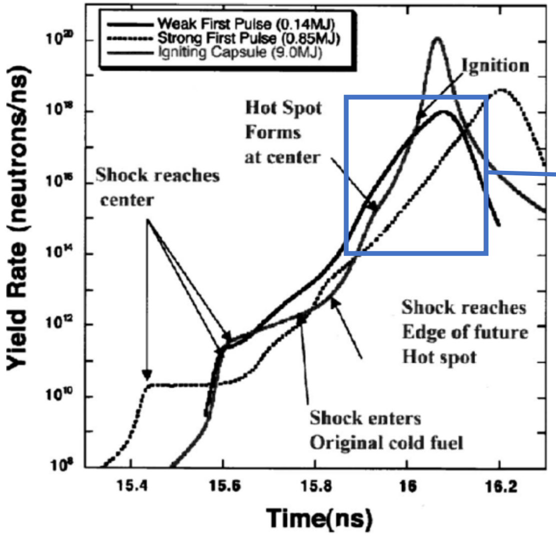


FIG. 1. Reaction history of an igniting and two failing NIF capsules.

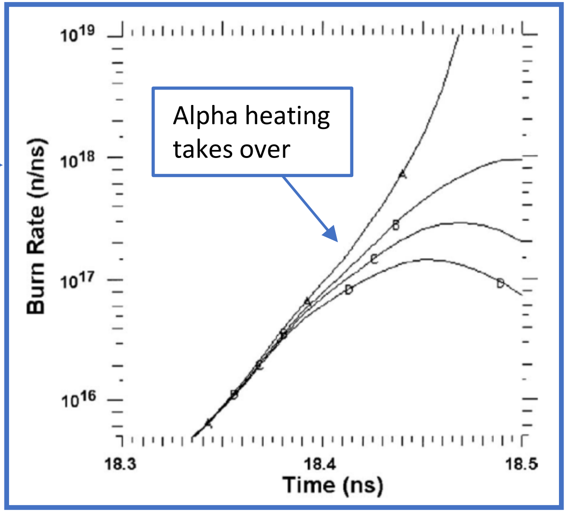


FIG. 6. Reaction histories from THD capsules with 1%, 10%, 20%, and 40% deuterium.

- With enough dynamic range and temporal resolution shock timing and hotspot formation can be seen
- Onset of Alpha heating can be resolved
- Causes for burn truncation can be investigated

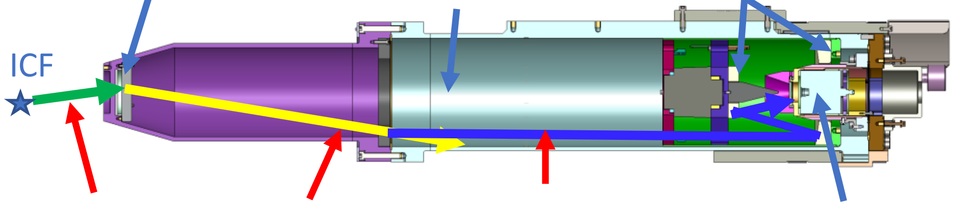
"Diagnosing ignition with DT reaction history", D. Wilson et al. Rev. Sci. Instrum. 79, 10E525 (2008)

High demands on diagnostic performance:

- Burn width at ignition might get as low as 10ps
- Dynamic range for measuring onset of alpha heating ~3 orders of magnitude
- Dynamic range for hotspot formation ~5 orders of magnitude

Gas Cherenkov Detectors (GCD) provide clean fusion reaction rate measurements

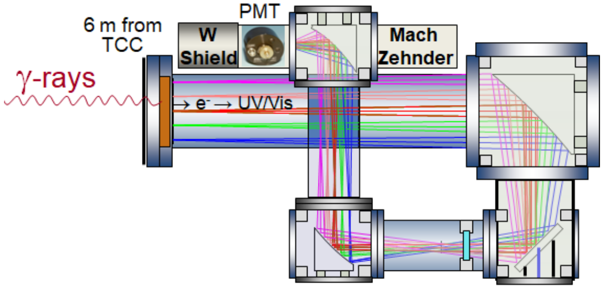
GCD-3:

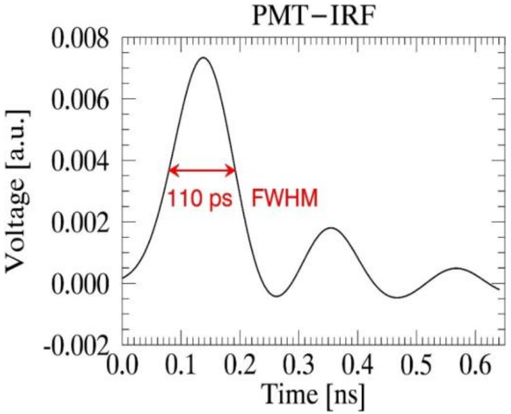


- Measurement threshold set by gas pressure
- Cherenkov process inherently fast
  <10 ps @ 8 MeV threshold
- Cherenkov signal delayed by 0.75 ns via Cassegrain optic
- Photomultiplier Tube (PMT) limits temporal resolution to ~100 ps

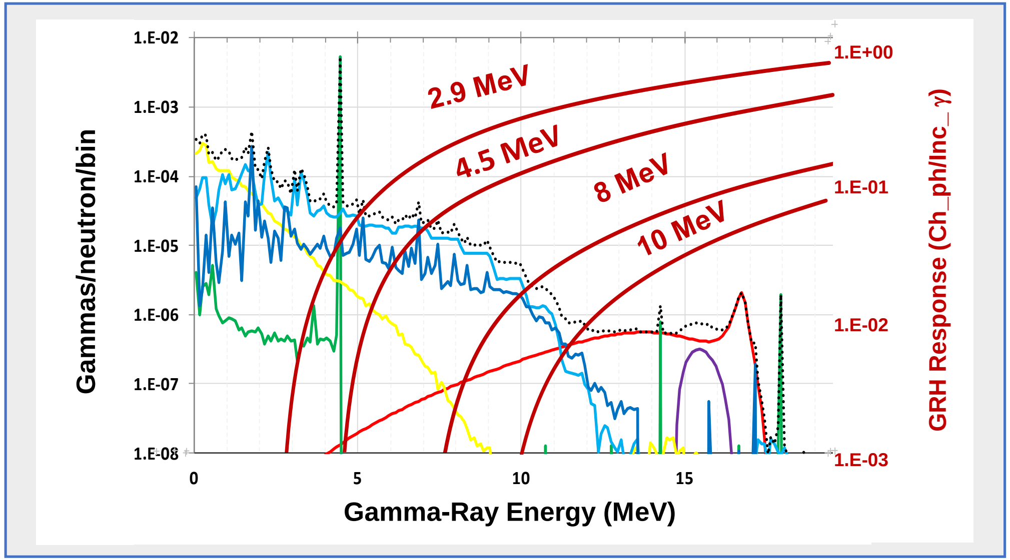
Sister instrument GRH:

- Four identical GCDs
- Same working principal as GCD-3





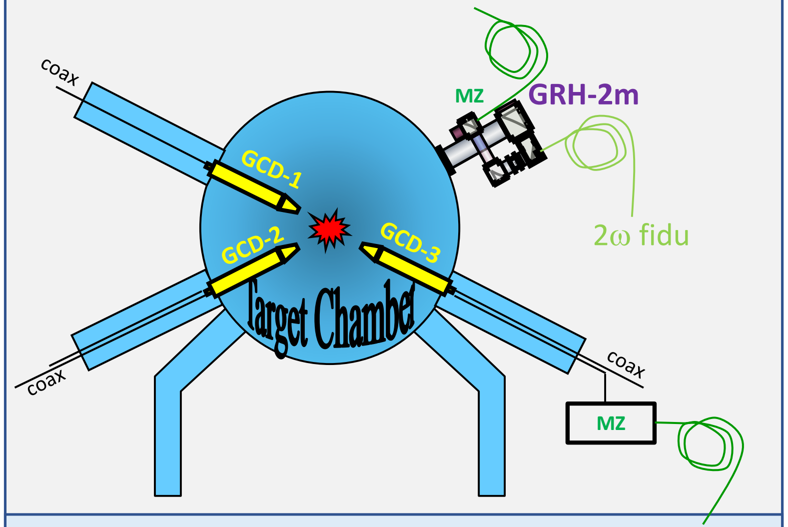
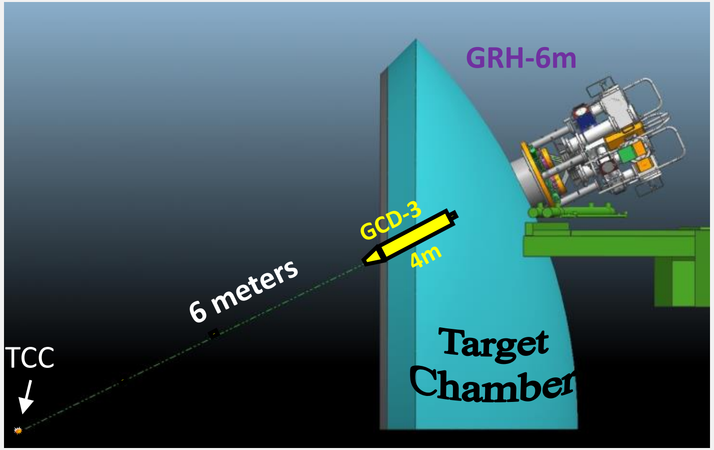
GCD thresholding capability results in a low background fusion burn rate measurement



- By thresholding out low energy background only DT fusion signal is measured
- Lower threshold allows for measuring carbon ablator performance (areal density)
- Energy spectrum and endpoint energy of x-ray sources can be measured (Cygnus, NRL, Z-machine)

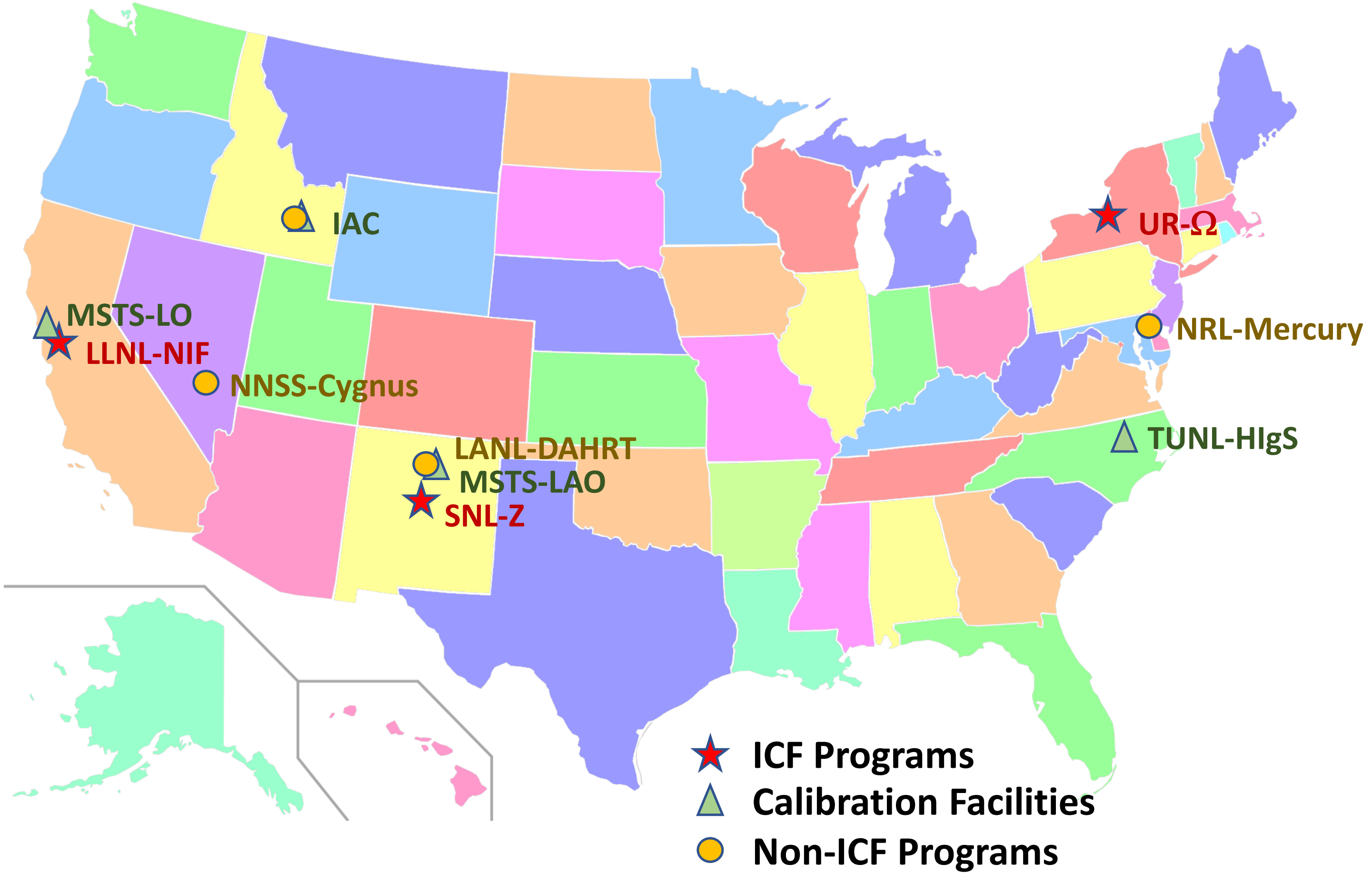
NIF Hohlraum/TMP

Gas Cherenkov Detectors have been in operation for many years now at OMEGA (2000) & NIF (2010)

OMEGA-60	NIF
	
3 GCDs (20cm), 1 GRH (187cm)	1 GCD (390 cm), 4 GRHs (607 cm)

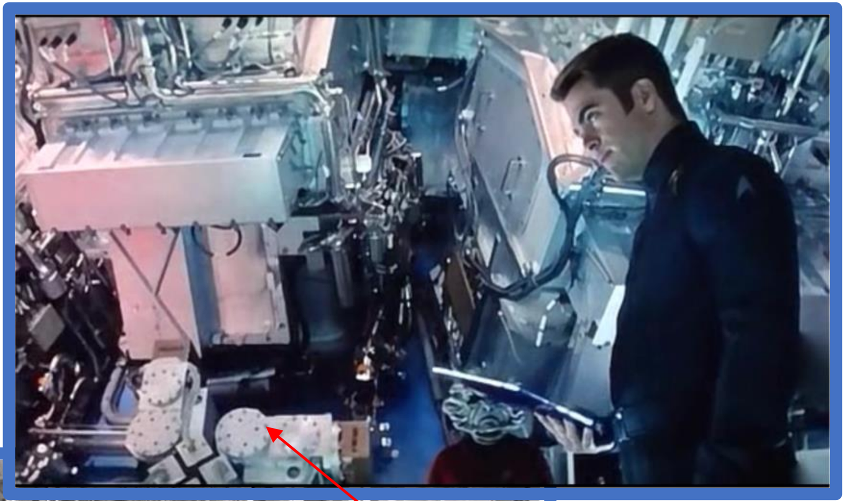
* GCD (Gas Cherenkov Detector), GRH (Gamma Reaction History)

LANL has extensive experience fielding Cherenkov Detectors

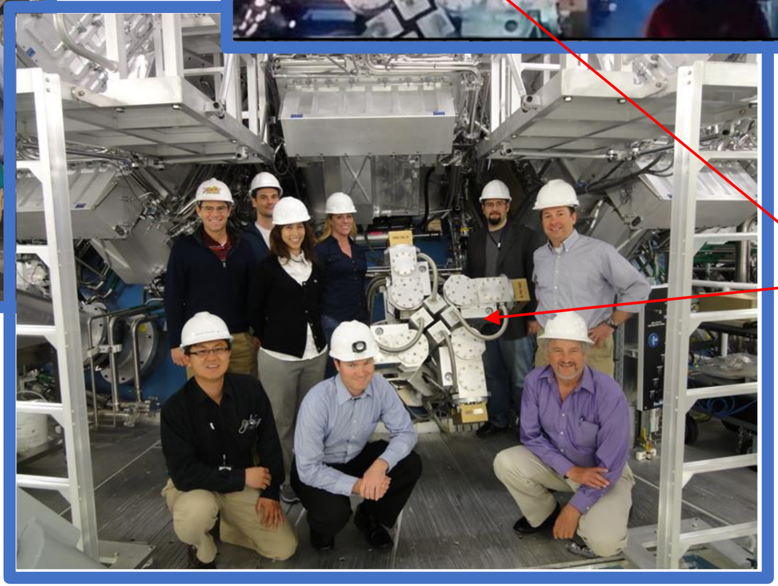


Gamma Team boldly goes…

GCD at NIF



courtesy Scott Chambliss, Paramount Pictures and Bad Robot Productions



GRH at NIF

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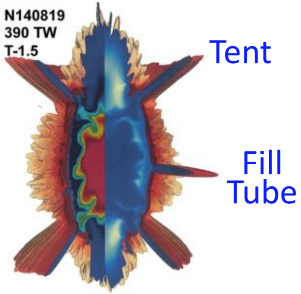
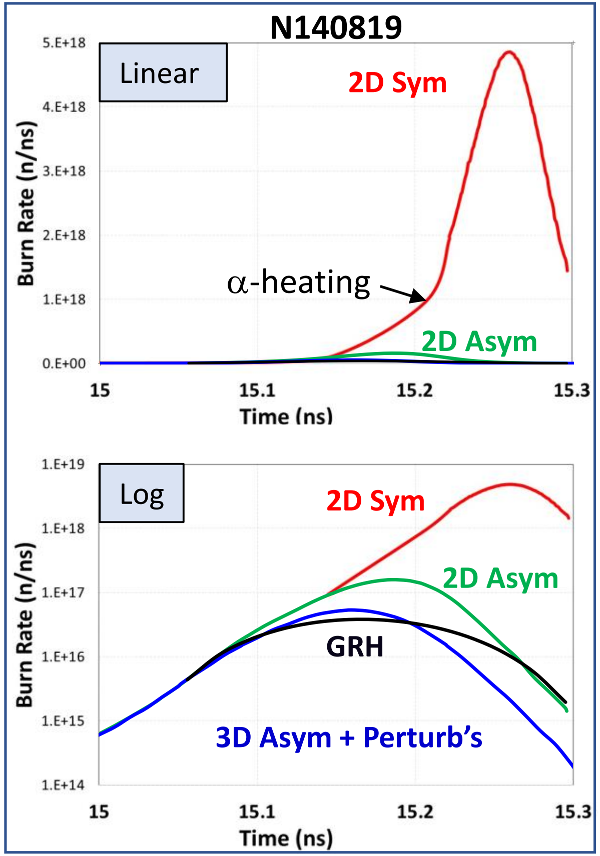
“Truncated” & “Prolonged” Burn apparent at NIF

Source	Y_{DTn}	BW (ps)	Comments
2D Sym.	3.7e17	60	~1D, ignites
2D Asym.	1.5e16	100	P2 tuned
3D Asym. + Perturb’s	5.5e15	110	~BT tuned
Data (GRH)	5.5e15	147	Always wide!

3D Asym + Perturbations



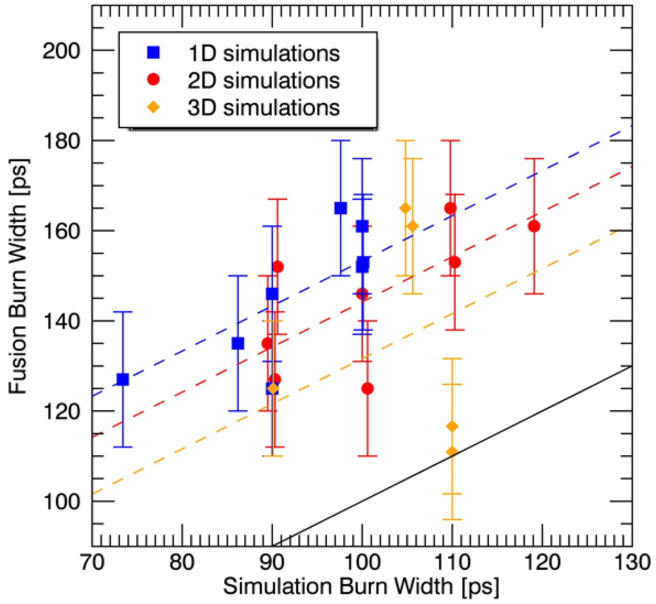
Courtesy of D. Clark



Increased temporal resolution will provide better insight

Burn width measurements are always wider than simulations predict

DTγ burn widths vs simulations



Simulations courtesy of D. Clark (LLNL)

Post-shot simulation results of HDC shots compared to DT burn widths measured by GRH:

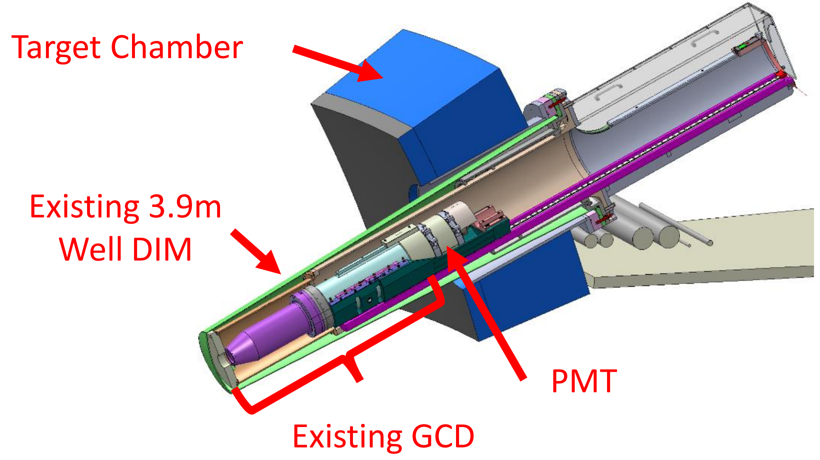
- 1D simulations are always narrower by ~50 ps than measured DT burn widths
- 3D simulations still give burn widths ~30 ps narrower than measured DT burn widths

Can we extrapolate to ignition experiments if simulations are not capturing burn width?

Simulations are missing a piece of physics in ICF implosions

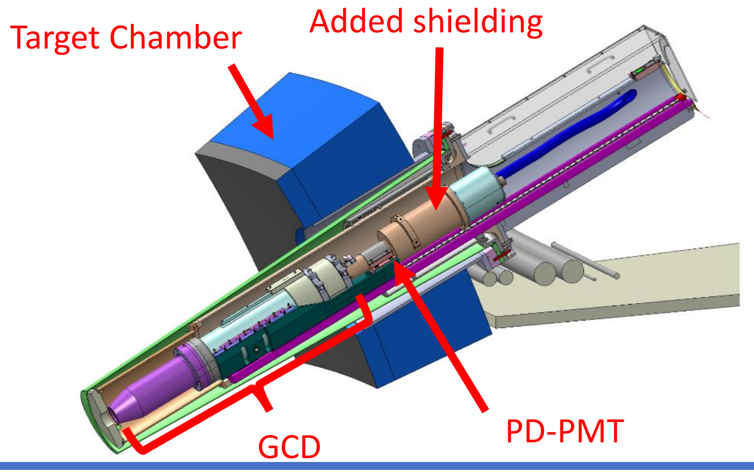
Enhanced Gamma Reaction History at NIF is divided into three phases

Phase I: Existing GCD-3 with regular PMT brought from OMEGA to NIF



- Background evaluation for Super GCD design
- Test bed for fast optical detector (PD-PMT)

Phase II: Develop and apply Pulse-Dilation PMT



- Measure first highly resolved gamma reaction histories

Phase III: Super GCD & Chamber insertion

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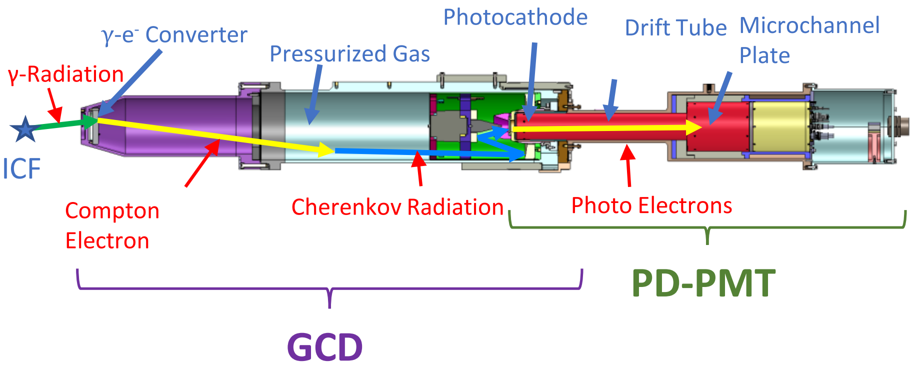
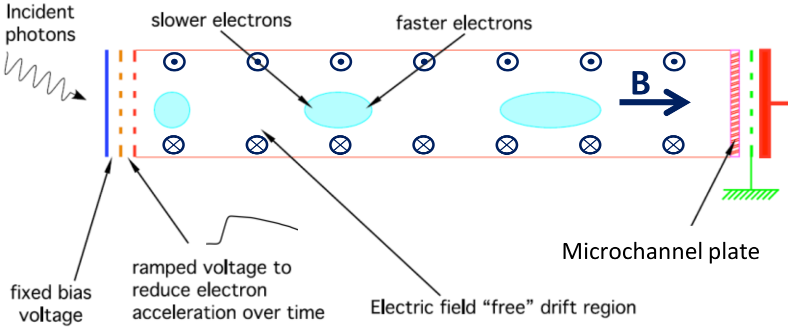
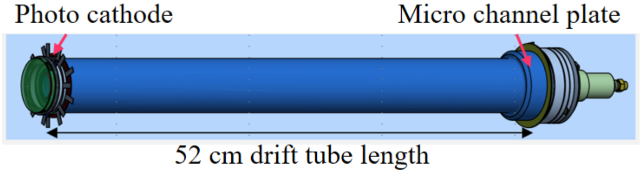
Pulse Dilation - Photomultiplier Tube (PD-PMT) stretches the signal yielding temporal magnification



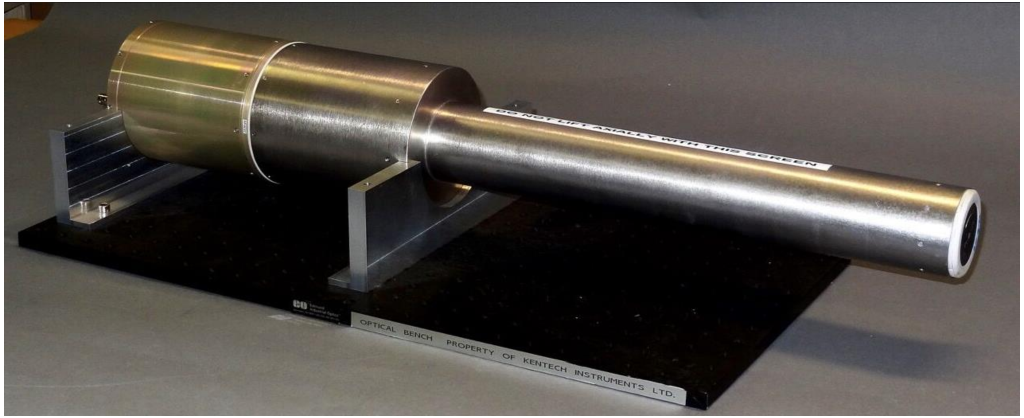




- Radiation hard (no phosphor, no CCD)
- Dilation factor up to 40x feasible
- Temporal resolution of 10 ps feasible
- More accurate measurement of burn width

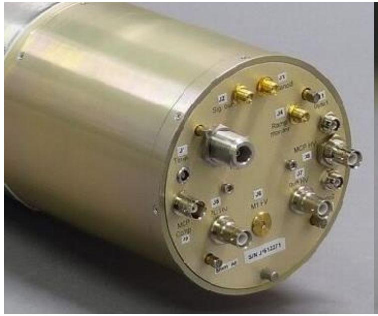
Burn profile can be resolved for the first time

Pulse Dilation - Photomultiplier Tube for GCD-3



Pulse Dilation – Photomultiplier tube (PD-PMT)

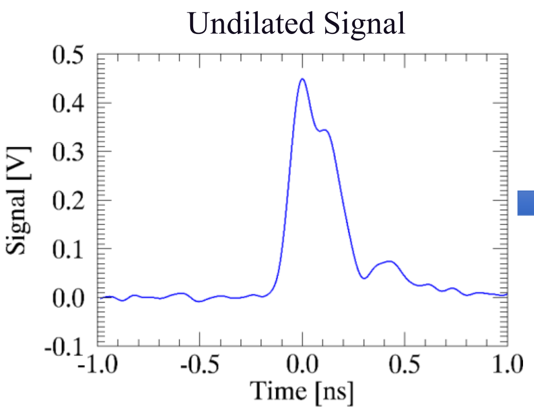
Length: 71 cm
Diameter front: 6 cm
Diameter back: 12 cm

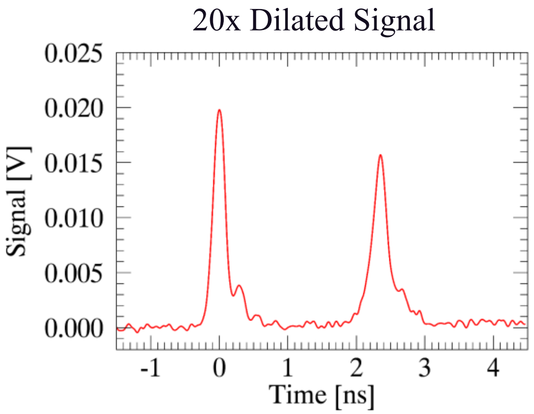

PD-PMT connectors

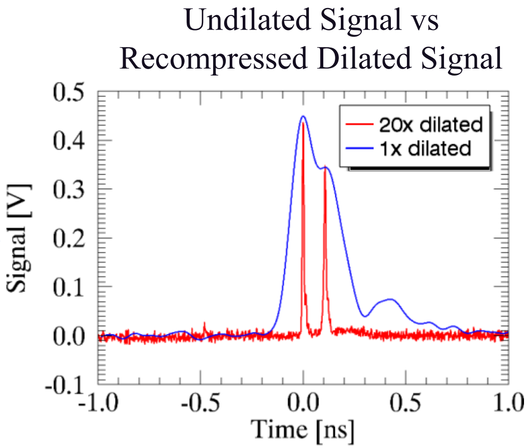
PD-PMT controller

LANL lead the development of PD-PMTs. They are now a commercially available product.

What does PD-PMT do?







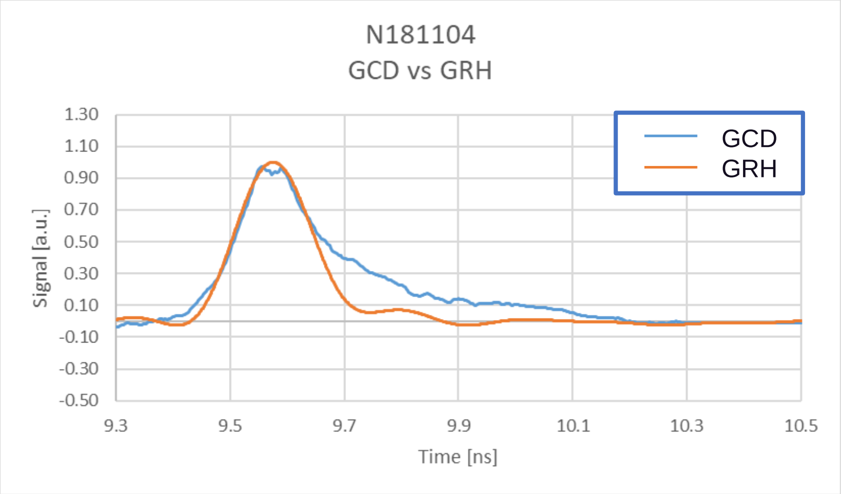
- Two laser pulses 12ps FWHM separated by 135ps
- Not resolvable without dilation

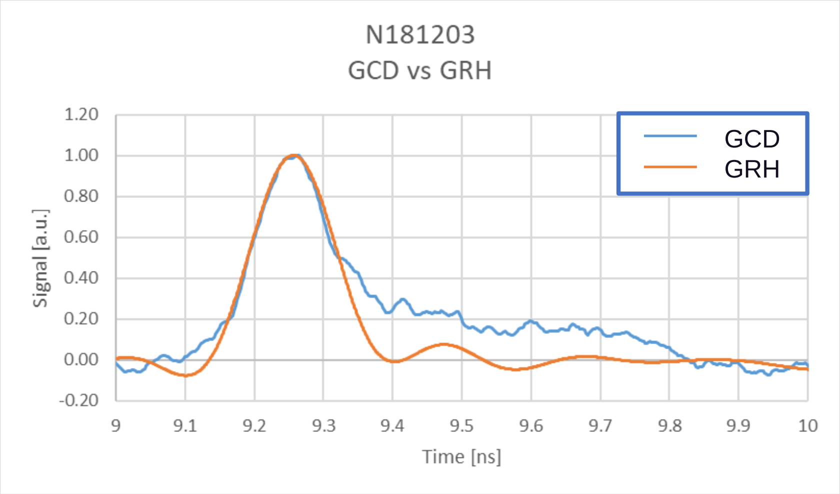
- ~20x dilation shows two separated pulses
- Signal stretched by dilation factor
- Amplitude decreased by dilation factor

- Recompression needed to get back to undilated signal
- Peaks well separated

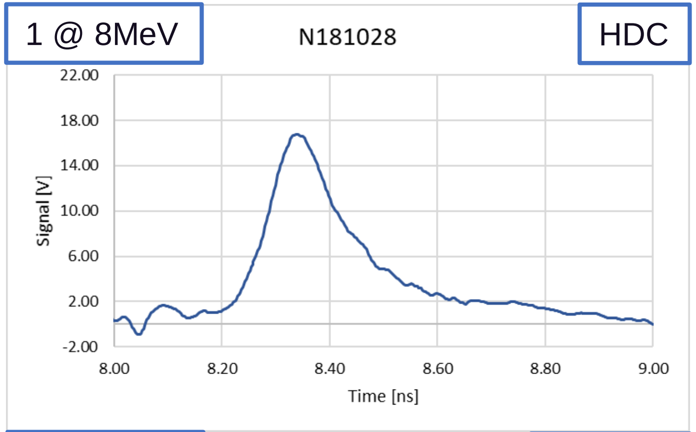
The burn width of GCD agree with GRH within error bars

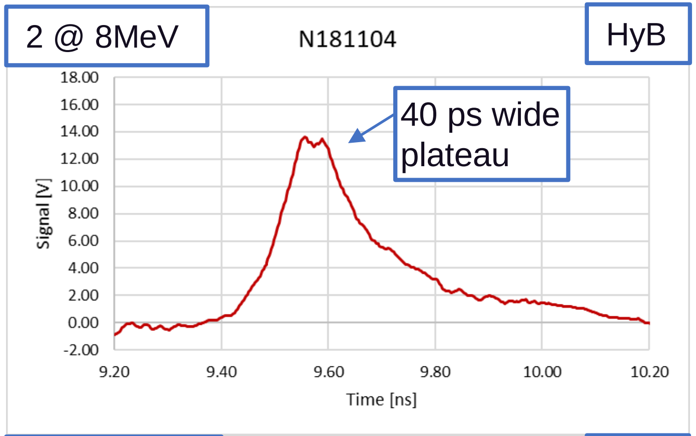
	Shot Number	Experiment	GRH BW	GCD BW	ΔBW
1	N181028-001-999	I_Int_DT_HDCScaleUp_S10	149	154	5
2	N181104-002-999	I_Int_DT_HyB_S08a	156	167	11
3	N181118-002-999	I_Int_DT_CH_ALD_S01a	157	142	-15
4	N181203-001-999	I_Int_DT_HyB_S10a	136	134	-2

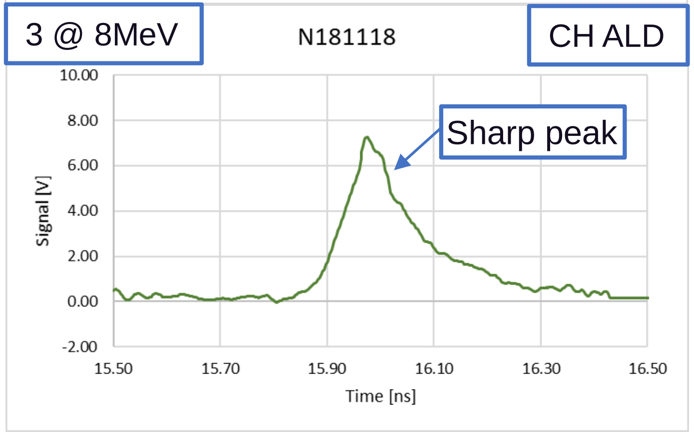


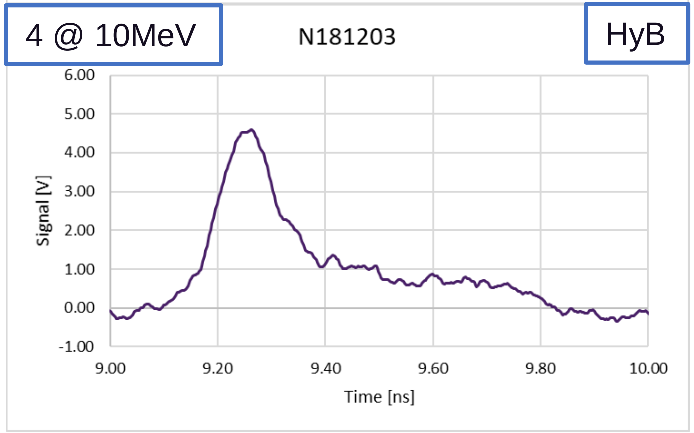


DT gamma reaction histories reveal high frequency features

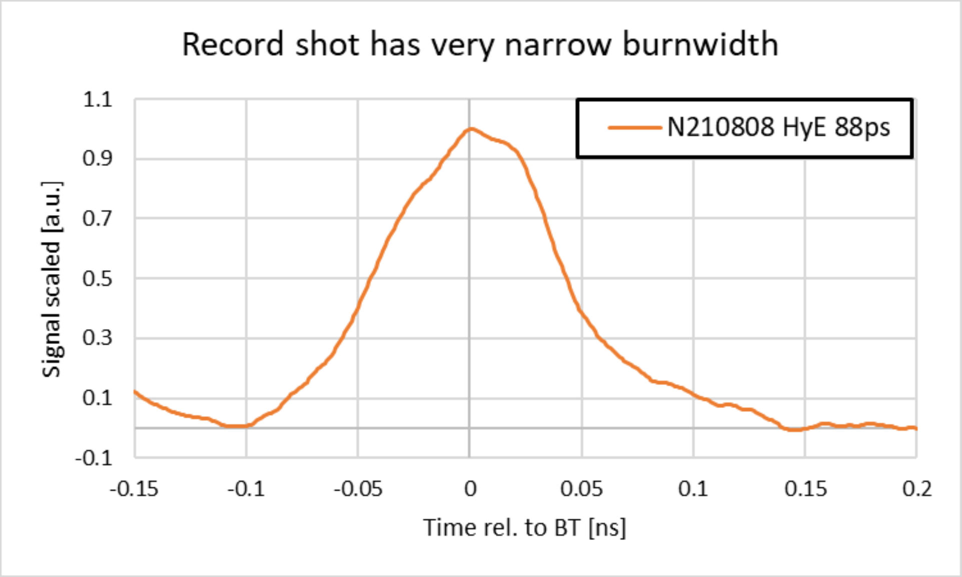








Latest NIF high yield shot showed drastic performance increase
LANL diagnostics collected data successfully



Narrowest burn width ever measured at NIF

GRH provided bang time and yield estimate successfully:

- Bang time 9.27 +- 0.07ns
- Yield ~3E17 neutrons

GCD provided burn width:

- Burn width 88ps +-15ps

NIF performance gains:

- ~4E17 neutron yield
- New physics regime
- 6x more yield than half a year ago
- 4x more energy yield than absorbed by the capsule

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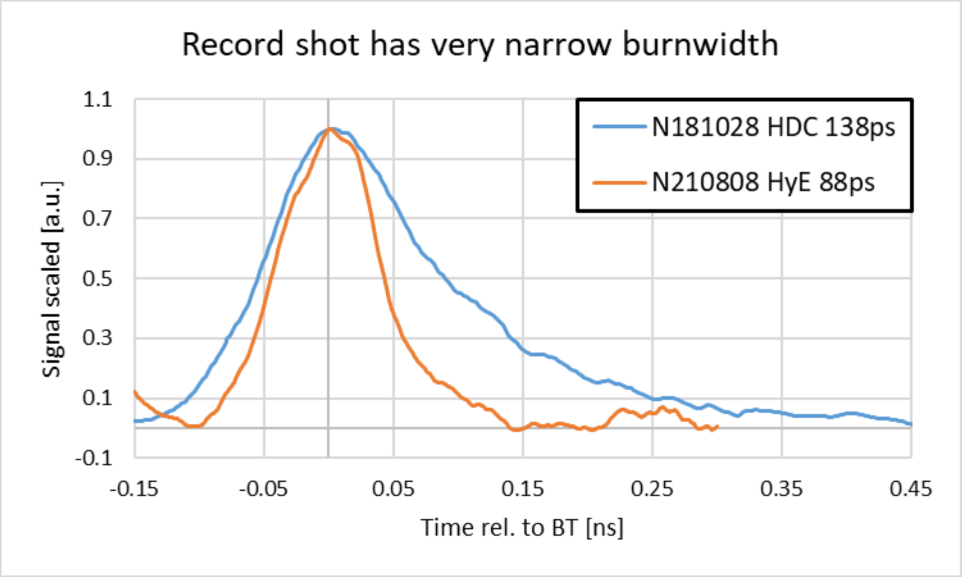

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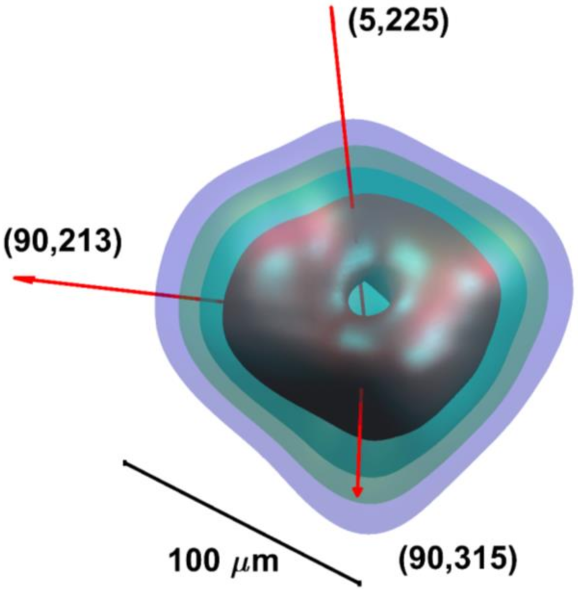
3D reconstruction of fusion neutron emission

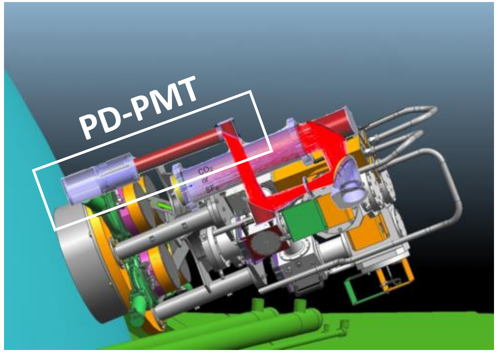


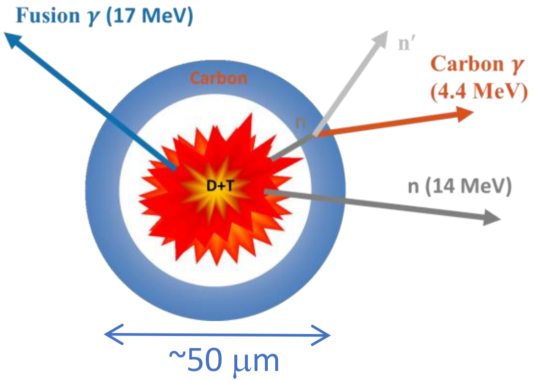
Outlook

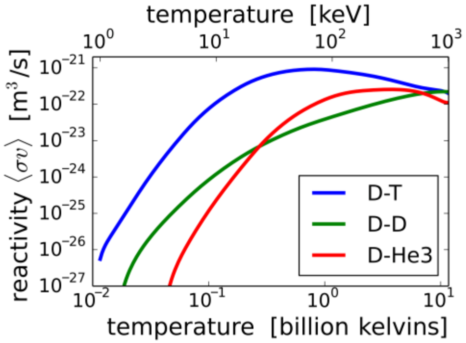
- **PD-PMT on GRH**
  - Lower background DT fusion reaction history than GCD-3
  - Improved ablator measurement

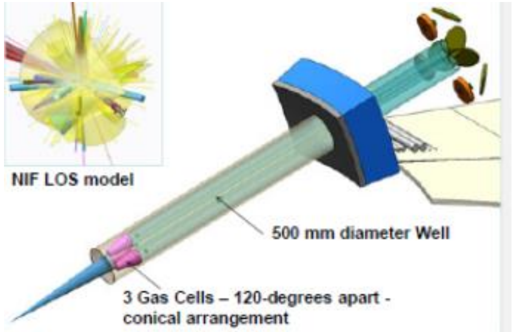
- **Co-timed PD-PMTs**
  - Pusher performance measurements
  - Ion temperature as function of time

- **High sensitivity Super-GCD**
  - New realms of physics









Conclusion

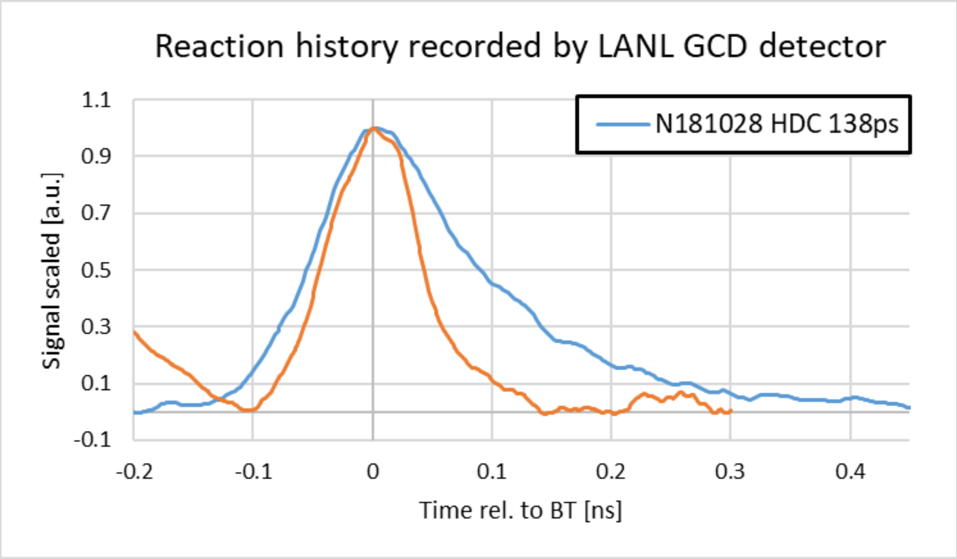
- **Latest high yield shot at NIF seems to have reached new physics regime**
  - Alpha heating dominated yield
  - Might have achieved burn propagation

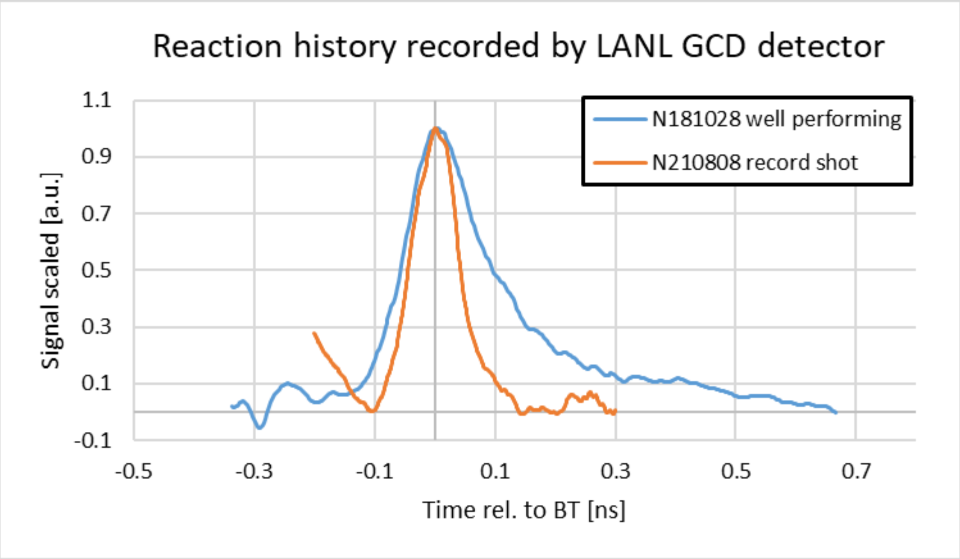
- **DT fusion reaction history provides crucial data for igniting targets**
  - Bang time and burn width were measured by GCD-3 and GRH
  - Burn width down to ~10ps can be resolved
  - Onset of alpha heating might be seen on future shots

- **The Pulse Dilation – PMT greatly improves the capabilities of GCDs**
  - Temporal resolution improved by an order of magnitude
  - Advanced ablator performance measurement

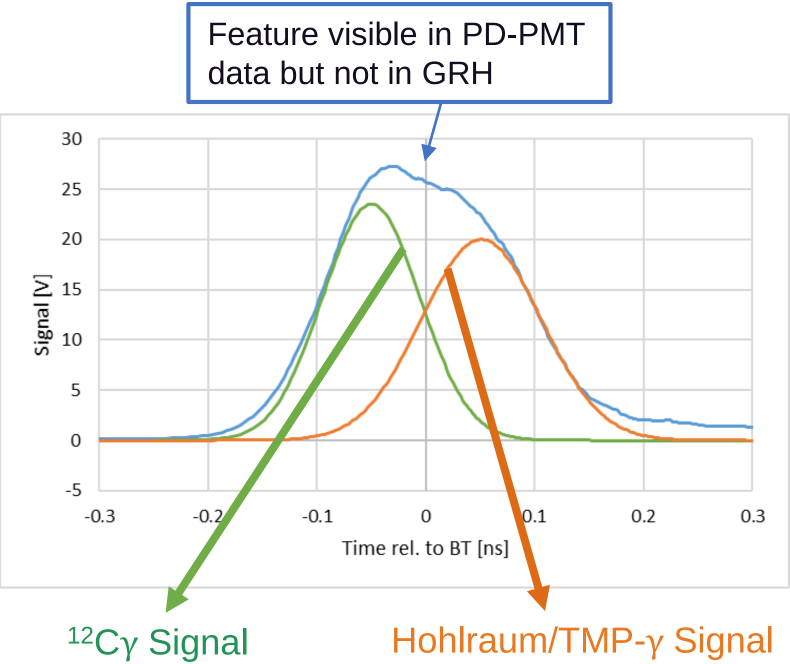
Backup

Results N210808



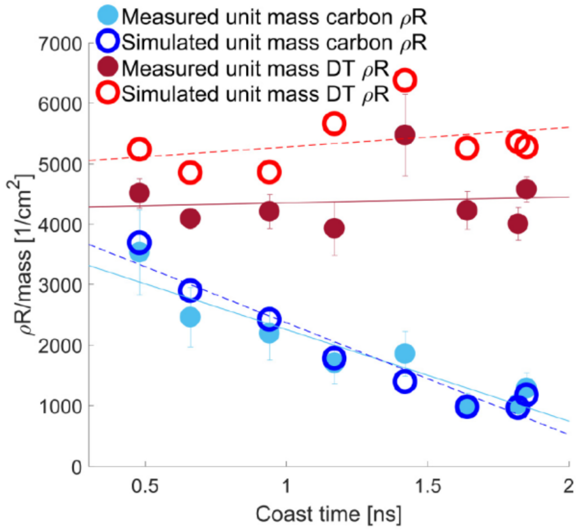


First dilated data taken at 2.9 MeV threshold measuring ^{12}C and Hohlraum/TMP gammas on Big Foot N180930

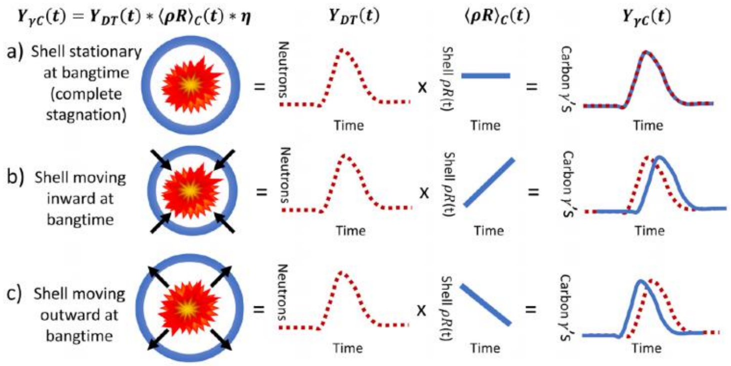


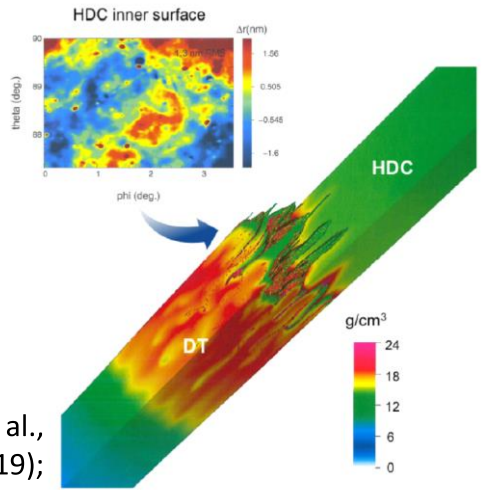
- Separation of ^{12}Cγ signal is needed for ablator areal density measurement
- Structure in the 2.9 MeV signal allows for better separation of the ^{12}Cγ and Hohlraum/TMP signal
- With shorter burn width the separation of ^{12}Cγ and Hohlraum/TMP signal will improve

PD-PMT allows improved ablator areal density measurements



K. D. Meaney, et al., PHYSICAL REVIEW E **101**, 023208 (2020)



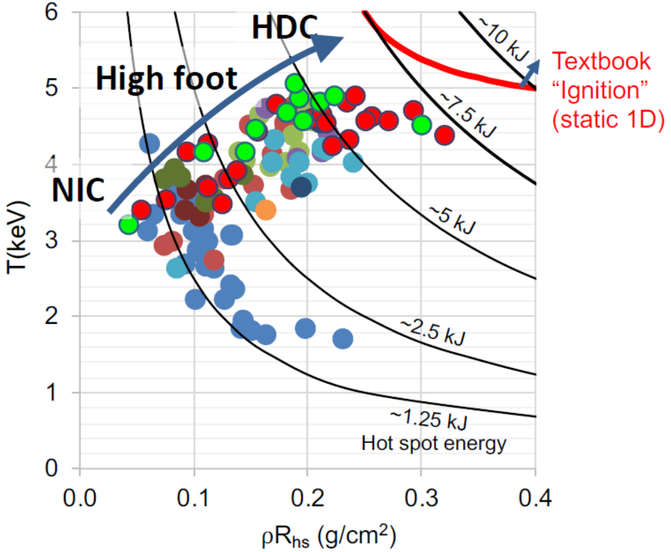


C. Clark, et al.,
Phys. Plasmas **26**, 050601 (2019);

Los Alamos
NATIONAL LABORATORY

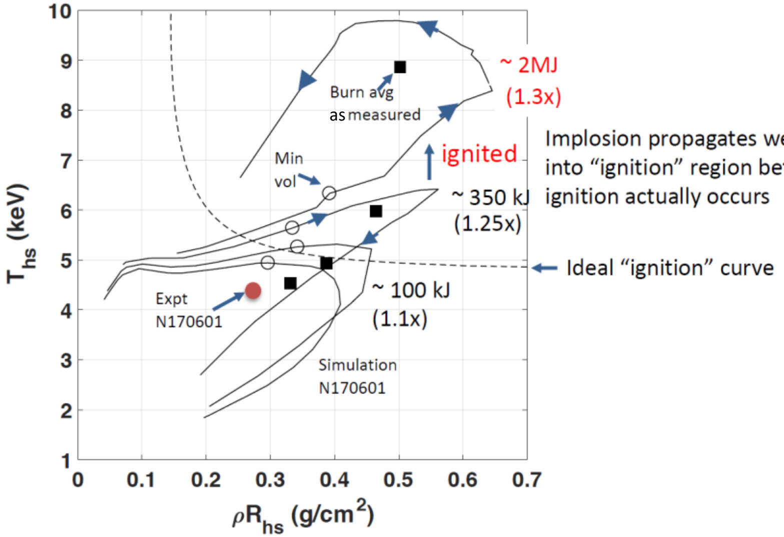
Progress of high yield experiments at NIF

Progression of DT hot spot properties towards ignition regime



Estimate need ~ 1.5-2X energy coupled to hot spot

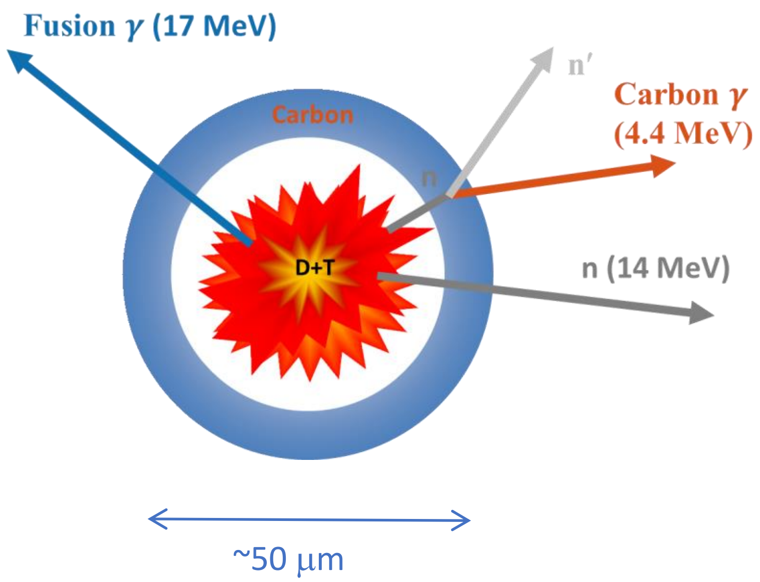
Detailed 2D simulation trajectories of N170601 and hydroscales



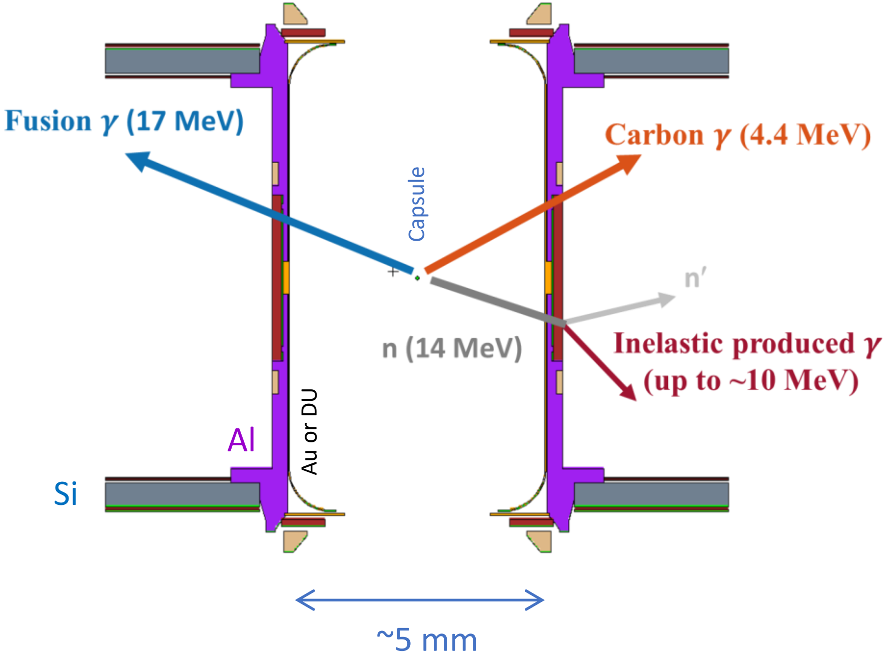
Courtesy of John Edwards

DT fusion neutrons induce gamma-rays as they pass through the capsule and Hohlraum/TMP

Capsule



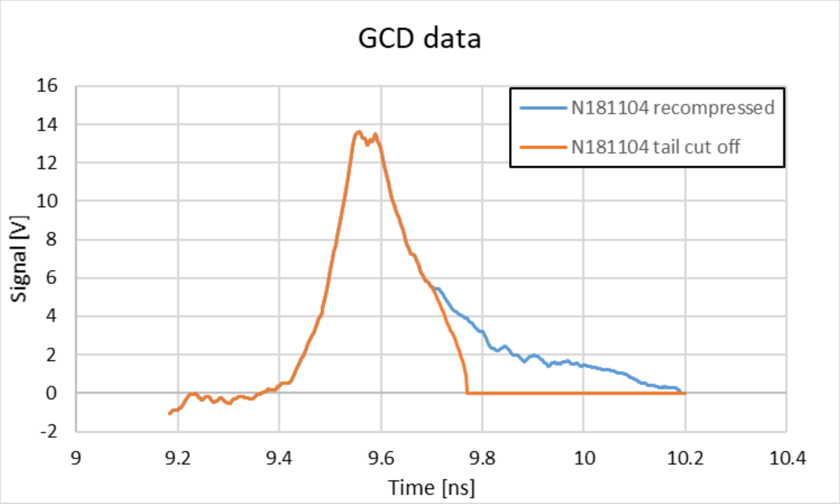
Hohlraum/
Thermomechanical Package (TMP)

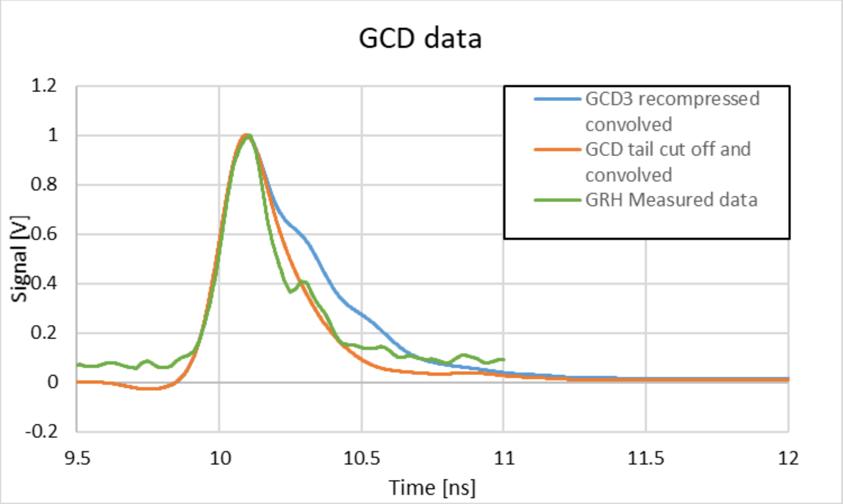


Tail in GCD-3 history is not matching GRH results

Test: Convolve GCD-3 data with GRH system IRF

Compare to raw GRH signal





When cutting the off the tail of GCD-3 at 30% of max convolved signals agree